The Muon Anomalous Magnetic Moment from a Generic Charged Higgs with SUSY

Chuan-Hung Chen[a] **and C. Q. Geng**[b]

[a]*Department of Physics, National Cheng Kung University*
Tainan, Taiwan, Republic of China

[b]*Department of Physics, National Tsing Hua University*
Hsinchu, Taiwan, Republic of China

Abstract

We study the contribution of a generic charged Higgs (H^+) to the muon anomalous magnetic moment a_μ with the SUSY soft breaking parameters. We find out that the deviation between the experimental data and the predicted SM value on a_μ can be explained by the two-loop charged Higgs diagrams even with $m_{H^+} \sim 400\ GeV$.

It is believed that the muon anomalous magnetic moment, $a_\mu \equiv (g_\mu - 2)/2$, would provide precision tests of the standard model (SM) and probe for new physics [1]. Recently, it has been measured at BNL [2] with the data

$$a_\mu^{exp} = 116\ 592\ 023(151) \times 10^{-11}\ . \tag{1}$$

The experimental value in Eq. (1) differs from that in the SM [2] despite of the several different theoretical predictions from hadronic contributions [3, 4]. In Ref. [2], it was reported that

$$\Delta a_\mu \equiv a_\mu^{exp} - a_\mu^{SM} = 426 \pm 165 \times 10^{-11}\ , \tag{2}$$

while a recent calculation [4] based on a different estimation from the hadronic part gave

$$\Delta a_\mu = 375 \pm 170 \times 10^{-11}\ . \tag{3}$$

The values in Eqs. (2) and (3) indicate a window for new physics at 2.6σ and 2.2σ levels, which are translated into

$$215 \times 10^{-11} \le \Delta a_\mu \le 637 \times 10^{-11}\ (90\%\ \text{CL})\ , \tag{4}$$

and

$$159 \times 10^{-11} \le \Delta a_\mu \le 599 \times 10^{-11}\ (90\%\ \text{CL})\ , \tag{5}$$

respectively. It is clear that both ranges in Eqs. (4) and (5) suggest the existence of new physics beyond the SM. However, one must caution about this less than 3σ result until the experiment of E821 at BNL is completed, which should increase the statistical significance at more than 6σ level [5], and the theoretical uncertainties from the hadronic part in a_μ^{SM} are further reduced.

Recently, various models, such as those with SUSY, scalar bosons, and extra dimensions, which could lead to $\Delta a_\mu = O(400 \times 10^{-11})$ have been explored [1, 6, 7, 8]. In particular, it is discussed extensively to use scalar Higgs bosons in SUSY-like theories as the viable candidates. In Refs. [7, 8], the possibilities of using light neutral Higgs bosons with a large $tan\beta$ to account Δa_μ at the one- and two-loop levels were studied. It is known that a large $tan\beta$ is interesting theoretically since the unification of bottom and tau Yukawa couplings and the explanation of the top to the bottom mass ratio are realized in GUTs if $tan\beta \sim O(50)$ [9]. With this possible large $tan\beta$, it is found that the mass for the scalar boson has to be less than 5 GeV [7] and that for the pseudoscalar 75 GeV with including the Barr-Zee type [10] of the two-loop diagrams [8]. One may conclude that Δa_μ cannot arise from either a scalar or pseudoscalar in the minimal supersymmetric model (MSSM) due to the experimental limits on the scalar and pseudoscalar masses, which are in the ranges of $85 - 95$ GeV [11, 12, 13].

In this paper, we would like to examine whether it is possible to use a charged Higgs boson in SUSY models to induce Δa_μ beyond the one loop level. It is known that the challenge with a charged Higgs in theories is how to escape the constraint from the experimental value of $B(B \to X_s \gamma) = 2.85 \pm 0.41 \times 10^{-4}$ [14] which is consistent with that of $3.29 \pm 0.33 \times 10^{-4}$ predicted in the SM. Following the analysis of [15, 16] with the next-to-leading order (NLO) QCD corrections, the lower limit on the charged Higgs mass in the two-Higgs doublet model (model II) is 450 GeV. However, the bound can be released in the framework

of supersymmetric theories because of the somewhat cancellation between the particle and its superpartner [17]. In Refs. [18] and [19], it has been demonstrated that the NLO contributions in a SUSY model with a sufficient large $tan\beta$ may be comparable as that from the leading order (LO). Thus, with choosing a proper sign of the Higgs mass mixing parameter μ, the charged Higgs and chargino contributions to $B \to X_s\gamma$ are suppressed. Furthermore, SUSY models without R-parity, such as those by including $\mu_i L_i H_d$, called bilinear terms, in the superpotential, can also allow a charged Higgs as light as 80 GeV by requiring the chargino mass $m_{\chi^\pm} > 90 GeV$ [20]. Another scenario to evade the constraint is proposed in Ref. [21], in which the b-quark mass is induced from radiative corrections so that the coupling $H^+\bar{t}_L b_R$ is generated from higher order effects and thus, the Wilson coefficient of C_7 for $b \to s\gamma$ is suppressed by $1/tan^2\beta$. This also implies that the bound on the charged Higgs mass can be lower without a fine tuning. Hence, the light charged Higgs is still viable in some of SUSY models and it could be reachable in future collider searches. In the following we shall concentrate on a generic charged Higgs in models with SUSY, whose lower mass limit is only constrained by the LEP experiments [22], *i.e.*,

$$m_{H^+} > 80.5 \ GeV \,. \tag{6}$$

The one-loop charged Higgs contribution to a_μ was studied previously [23, 24] and it was found that to accommodate the value of Δa_μ in Eq. (4) or (5), m_{H^+} has to be less than a few GeV even with a large $\tan\beta$ [7]. This contribution is clearly negligible if one uses the limit in Eq. (6). For the contribution to Δa_μ from the Barr-Zee type of the two-loop diagrams [10] with the charged Higgs in the loops similar to the one in Ref. [25], we find that it is still small.

Since the one and two loop diagrams mentioned above involve only the well known transition elements in which all couplings are almost fixed except $\tan\beta$, it seems to be impossible to generate a sizable Δa_μ via loops with a charged Higgs. However, it is interesting to ask whether there would exist some enhancement factors in some SUSY models with the charged Higgs so that Δa_μ could be large. In fact, as we are going to show next, such possibility could be realized by considering two-loop diagrams in which the charged Higgs couples to squarks but not quarks, and with introducing the SUSY soft breaking parameters for the effects of the SUSY broken in the low energy.

We start with the relevant couplings of the charged Higgs to squarks, the trilinear soft breaking terms, given by

$$\mathcal{L}_{soft} \quad = \quad A_U Y_{ij}^U \tilde{Q}_i H_U \tilde{U}^c + A_D Y_{ij}^D \tilde{Q}_i H_D \tilde{D}^c \,, \tag{7}$$

where $Y_{ij}^{U,D}$ denote the Yukawa couplings with i and j being the flavor indices, and $A_{U,D}$ are the SUSY soft breaking parameters. From Eq. (7), we see that the coupling for $H^+\tilde{t}_L^*\tilde{b}_R$ is $\sim m_b A_b tan\beta$. With the terms in Eq. (7), the effective vertex of $H^+ - \gamma - W^+$ can be induced as shown in Figure 1 in which squarks are in the loops.

In SUSY models, the main contributions to Δa_μ are with *chargino* − *sneutrino* and *neutralino* − *slepton* couplings in loops [26]. One can show that the former will become dominant, which is proportional to $(m_\mu/m_{SUSY})^2 tan\beta$ if $tan\beta$ is large [26] where m_{SUSY} denotes the the mass of the sneutrino or chargino. For $tan\beta >> 1$, Δa_μ can set a lower bound on the mass of the sneutrino while the chargino is light. To concentrate on the charged Higgs effect, we assume that both sneutrino and slepton masses are large enough

so that their effects are negligible for Δa_μ, but we still need a light chargino and squarks to satisfy the constraint from $b \to s\gamma$.

The effective Lagrangian which describes the interaction of the charged Higgs to squarks and leptons in terms of their weak eigenstates is

$$\mathcal{L}_{H^+} = \frac{g}{\sqrt{2}m_W} \left[m_t \mu \tilde{Q}_{ti}^* \tilde{Y}_{ij} \tilde{Q}_{bj} + m_l \tan\beta \bar{\nu}_l P_R \ell \right] H^+ + h.c.$$

with

$$\tilde{Y} = \left[\begin{array}{cc} -\hat{m}_W^2 \sin 2\beta + \hat{m}_b' \hat{m}_b \tan\beta + \hat{m}_t \cot\beta & \hat{m}_b' \left(1 - \hat{A}_b \tan\beta \right) \\ 1 - \hat{A}_t \cot\beta & 2\hat{m}_b / \sin 2\beta \end{array} \right] \tag{8}$$

where $\tilde{Q}_t^* = (\tilde{t}_L^*, \tilde{t}_R^*)$ and $\tilde{Q}_b^T = (\tilde{b}_L, \tilde{b}_R)$ are the stop and sbottom, the parameters with a hat are renormalized by the μ parameter except $\hat{m}_W^2 = m_W^2 / m_t \mu$ and $\hat{m}_b' = m_b / m_t$, and $\hat{A}_{t,b}$ are related to the SUSY soft breaking terms, respectively. From Eq. (8), we see that $\tilde{Y}_{LR} \sim \hat{A}_b \tan\beta$, which contains not only $\tan\beta$ but also a large factor from the soft SUSY breaking parameters. The relevent squark mass matrix can be expressed by [28]

$$M_{\tilde{q}}^2 = \left[\begin{array}{cc} m_{\tilde{q}_L}^2 & m_q \mu \hat{a}_q \\ m_q \mu \hat{a}_q & m_{\tilde{q}_R}^2 \end{array} \right] \tag{9}$$

with

$$\begin{array}{rcl} m_{\tilde{q}_L}^2 & = & M_{\tilde{q}_L}^2 + m_q^2 + m_Z^2 \cos 2\beta \left(I_q^3 - Q_q \sin^2 \theta_W \right), \\ m_{\tilde{q}_R}^2 & = & M_{\tilde{q}_R}^2 + m_q^2 + Q_q m_Z^2 \cos 2\beta \sin^2 \theta_W, \\ \hat{a}_b & = & \hat{A}_b - \tan\beta, \\ \hat{a}_t & = & \hat{A}_t - \cot\beta \end{array} \tag{10}$$

where $M_{\tilde{q}_{L,R}}^2$ arise from the SUSY broken effects. Hence, the physical sbottom and stop masses can be found as

$$m_{\tilde{q}_{1,2}}^2 = \frac{1}{2} \left(m_{\tilde{q}_L}^2 + m_{\tilde{q}_R}^2 \mp \sqrt{\left(m_{\tilde{q}_L}^2 - m_{\tilde{q}_R}^2 \right)^2 + 4 m_q^2 \mu^2 \hat{a}_q^2} \right). \tag{11}$$

In our discussion, we take $m_{\tilde{q}_L}^2 \simeq m_{\tilde{q}_R}^2 \simeq m_{\tilde{q}}^2$ so that $m_{\tilde{q}_{1,2}}^2 \simeq m_{\tilde{q}}^2 \mp |m_q \mu \hat{a}_q|$. For ensuring the squark masses being positive, we require that $|m_q \mu \hat{a}_q| < m_{\tilde{q}}^2$. By using $\mu \simeq 2\,TeV$, $\hat{A}_q \simeq -2$ and $\tan\beta \simeq 40$, and choosing $m_{\tilde{b}} \simeq 645\,GeV$ and $m_{\tilde{t}} \simeq 820\,GeV$, one can show that the lightest sbottom and stop can be $\sim 100\,GeV$.

From Figure 1, the gauge invariant form of the effective coupling for $H^+ - \gamma - W^+$ with squarks in the loops is expressed as [27]

$$\Gamma^{\mu\nu} \left(q^2 \right) = N_c \frac{c_{\tilde{t}} s_{\tilde{b}} \alpha_{em} e m_b \mu \hat{A}_b^*}{4 m_W \pi \sin^2 \theta_W} \int_0^1 dx \frac{x(1-x)(Q_t(1-x) + Q_b x)}{\left(m_{\tilde{t}_1}^2 - q^2 x \right)(1-x) + m_{\tilde{b}_1}^2 x} \left[q^\mu k^\nu - q \cdot k g^{\mu\nu} \right] \tag{12}$$

where $N_c = 3$, $Q_t = 2/3$ and $Q_b = -1/3$ are stop and sbottom charges, and $c_{\tilde{t}} = \cos\theta_{\tilde{t}}$ and $s_{\tilde{b}} = \sin\theta_{\tilde{b}}$ express the mixings of left and right squarks in $\tilde{t}_1 = c_{\tilde{t}} \tilde{t}_L + s_{\tilde{t}} \tilde{t}_R$ and $\tilde{b}_1 = c_{\tilde{b}} \tilde{b}_L + s_{\tilde{b}} \tilde{b}_R$, respectively. In the following discussions, we shall assume that $\tilde{t}_1$ and $\tilde{b}_1$ are the lightest

squarks and use $c_{\tilde{t}}s_{\tilde{b}} = 0.5$ [12]. From Eq. (12), the two-loop contributions to Δa_μ are found to be

$$\triangle a_l = \frac{N_c c_{\tilde{t}} s_{\tilde{b}} \alpha_{em}^2 \tan^2\beta}{16\pi^2 \sin^4\theta_W} \frac{m_b \mu Re(\hat{A}_b^*)}{m_W^2} \frac{m_l^2}{m_{H^+}^2}$$

$$\times \left[Q_t J\left(\frac{m_W^2}{m_{H^+}^2}, \frac{m_{\tilde{t}_1}^2}{m_{H^+}^2}, \frac{m_{\tilde{b}_1}^2}{m_{H^+}^2}\right) + Q_b J\left(\frac{m_W^2}{m_{H^+}^2}, \frac{m_{\tilde{b}_1}^2}{m_{H^+}^2}, \frac{m_{\tilde{t}_1}^2}{m_{H^+}^2}\right) \right] \tag{13}$$

with

$$J(a, b, c) = \frac{1}{1-a}\left(I(b, c) - I(\frac{b}{a}, \frac{c}{a}) \right)$$

where

$$I(b, c) = \int_0^1 dx \frac{x(1-x)^2}{(b-x)(1-x)+cx} \ln\frac{x(1-x)}{b(1-x)+cx}.$$

It is worth to mention that by replacing the incoming (outgoing) muon and internal neutrino with b (s) and t quarks in the two-loop diagrams for a_μ, respectively, the decay of $b \to s\gamma$ can be generated. For a rough estimation, the Wilson coefficient C_7^{2-loop} associated with the operator $\bar{s}i\sigma_{\mu\nu}P_R b$ is positive, which has an opposite sign to that of the SM. That is, two-loop effects on $b \to s\gamma$ can reduce the other possible new physics contribution which are constructive with the SM so that $B \to X_s\gamma$ could still be consistent with the experimental data in the model. The detail analysis including one and two loops for $B \to X_s\gamma$ is beyond the scope of this paper.

In Figures 2 and 3, we show how the SUSY parameters enter in the contributions to Δa_μ. The results can be summarized as follows:

1. In Eq. (13), we factor out the μ parameter as the definition of a proper scale for the low energy SUSY so that the ratio $\hat{A}_b$ could be the guideline of the different scale needed between the electroweak and SUSY breaking. From Figure 2(a), in terms of the lower bound of 2.6σ level for Δa_μ, we know that μ can be 2 (0.5) TeV while $|A_b|_{min} \sim 9.0$ (36) TeV for $\tan\beta = 40$ and $M_{H^+} = 400$ GeV. We note that if we use a larger $\tan\beta$ and lighter M_{H^+}, the SUSY soft breaking parameter, A_b, can be further reduced. Following the analysis in Refs. [18] and [19], we choose sign(μ)>0 and sign(A_b)=sign (A_t)<0 to satisfy the bound of $B \to X_s\gamma$.

2. From Figure 2(b), it is clear that Δa_μ strongly depends on the value of $\tan\beta$. This is because that Eq. (13) is associated with a squared $\tan\beta$ arising from both couplings of $H^+\tilde{t}_L^*\tilde{b}_R$ and $H^+\bar{\nu}_L\ell_R$. This leads to the contribution increased by a factor 2 when replacing $\tan\beta = 40$ by 60.

3. According to Figure 3, if we use $\tan\beta \sim O(50)$ and the bound in Eq. (5), the squark mass can be as heavy as 150 GeV, while the charged Higgs mass is fixed to be 200 GeV. As known, the bound can be relaxed if the allowed SUSY breaking scale is higher.

Finally, we remark that the neutral Higgs can also contribute to Δa_μ through the coupling of the neutral Higgs and squarks similar to the charged Higgs mechanism above, given by

$$\mathcal{L}_{\tilde{f}\tilde{f}H^0} = \frac{g}{2M_W \sin\beta}(m_t A_t \sin\alpha + \mu\cos\alpha)(\tilde{t}_L^*\tilde{t}_R + \tilde{t}_R^*\tilde{t}_L)H^0$$

$$+ \frac{g}{2M_W \cos\beta}(m_b A_b \cos\alpha + \mu\sin\alpha)(\tilde{b}_L^*\tilde{b}_R + \tilde{b}_R^*\tilde{b}_L)H^0. \tag{14}$$

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In this case, there is no suppression arising from the W-boson mass unlike that with the charged Higgs. Therefore, the neutral Higgs effect usually can be larger than the charged Higgs one with the assumption of the same masses. The results can be easily obtained by setting $M_W = 0$ and substituting the relevant couplings in Eq. (13). Following our analysis above, we expect that the neutral scalar mass can be as heavy as 100 GeV in contrast with the case of the non-SUSY two Higgs doublet model (model II) where a light scalar mass, $M_{H^0} \leq 5$ GeV, is inevitable. For a pseudoscalar boson, due to the opposite sign in the couplings of the different chiral squarks, given by $(\tilde{q}_L^* \tilde{q}_R - \tilde{q}_R^* \tilde{q}_L) A^0$, the contribution to a_μ vanishes. On the contrary, if CP violating source is from the μ and $A_{t,b}$ terms, the CP violating observables, such as electric dipole moments (EDMs) of fermions, can arise from diagrams with the pseudoscalar.

In sum, we have analyzed the contribution of a generic charged Higgs to the muon anomalous magnetic moment in the SUSY model. We have illustrated that the experimental value of a_μ can be explained by the two-loop charged Higgs diagrams without a further fine tuning and the allowed parameter spaces are relatively large. For evading the strong constraints of $B \to X_s \gamma$ on m_{H^+}, the chargino and squarks are as light as charged Higgs and these conditions are detectable in present and future colliders. Due to the enhancements of A_b and $\tan \beta$, the mass of the charged Higgs could be over 400 GeV with proper values of other parameters.

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Figure Captions

Figure 1:   Feynman diagrams for effective vertices of $H^+ - \gamma - W^+$ where squarks are in the internal loops.

Figure 2: Δa_μ (in units of 10^{-9}) as a function of the charged Higgs mass with $\mu = 2\,TeV$ and $m_{\tilde{q}_1} = 110\,GeV$. The dashed, solid, dot-dashed and dotted lines stand for (a) $\hat{A}_b = -1.5, -3.0, -4.5, -6.0$ with $\tan\beta = 40$ and (b) $\tan\beta = 30, 40, 50$ and 60 with $\hat{A}_b = -2.0$, respectively.

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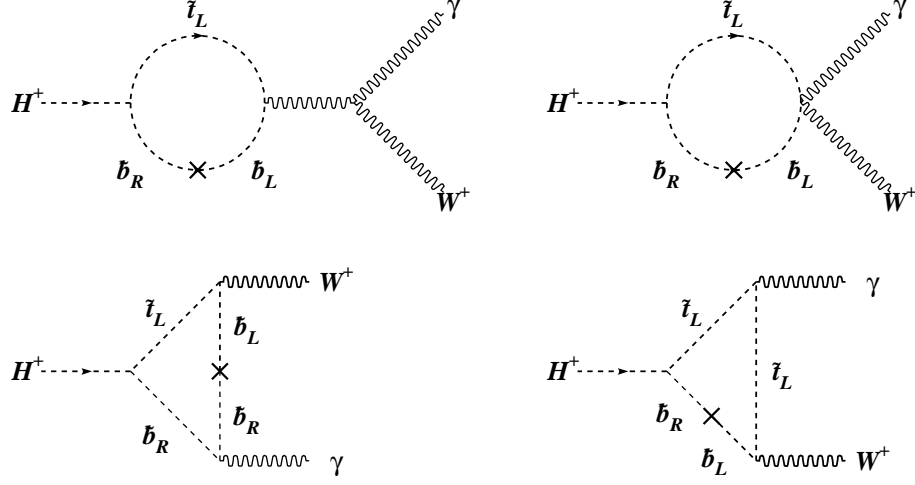
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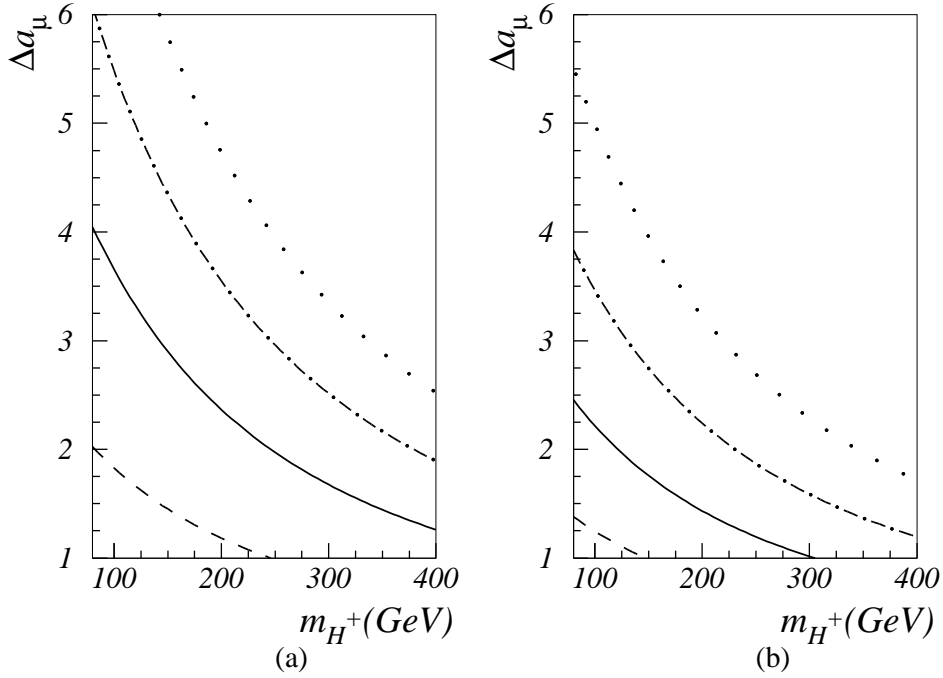

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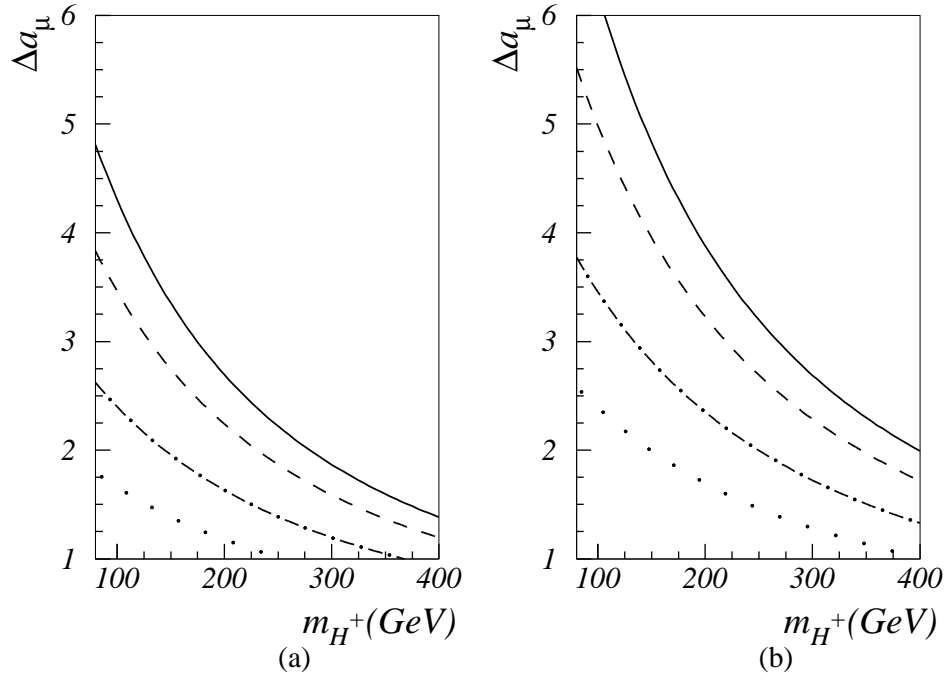
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